CGI Polarization Requirements: impact on hardware and concept of operations

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Work in Progress

CGI Polarization Requirements

- **MRD-451: Polarization of Disks:** “The Coronagraph Instrument shall be able to map the linear polarization of a circumstellar debris disk that has a polarization fraction greater or equal to 0.3 with an uncertainty of less than 0.03 in CGI Filter Band 1 and CGI Filter Band 4, assuming SNR of 100 per resolution element.”

- ~~**MRD-454: Telescope** [illegible] nstrument shall be able to measure the co[illegible] incident light in two orthogonal polari[illegible]~~

CGI Polarization Requirements

- **MRD-451: Polarization of Disks:** "The Coronagraph Instrument shall be able to map the linear polarization of a circumstellar debris disk that has a polarization fraction greater or equal to 0.3 with an uncertainty of less than 0.03 in CGI Filter **Band 1** and CGI Filter **Band 4**, assuming SNR of 100 per resolution element." **Traces back to PLRA BTR7:**

BTR7: : (High-Contrast Extended Source Imaging and Polarimetry)
WFIRST shall be able to map the extended surface brightness from 0.6″ to 1.3″ around a host star with V magnitude as dim as 5, at an integrated surface brightness per resolution element sensitivity equivalent to a source-to-star flux ratio as faint as 5x10-8 with an SNR of at least 10, and be able to map a linear polarization with a polarization fraction ≥ 0.3 with a systematic uncertainty of less than 0.03.

The SB sensitivity and polarization requirements are separate, i.e. OK to be demonstrated on different objects
Spirit is to keep the linear polarization fraction (LPF) measurement ***systematics*** *below 0.03.*

Please see John Krist's presentation regarding SB sensitivity (CGI contrast performance) aspect.

Clarifying MRD-451

MRD-451: Polarization of Disks: "The Coronagraph Instrument shall be able to map the linear polarization of a circumstellar debris disk that has a polarization fraction greater or equal to 0.3 with an uncertainty of less than 0.03 in CGI Filter Band 1 and CGI Filter Band 4, assuming SNR of 100 per resolution element."

- Both Filter 1 (575nm 10%) & Filter 4 (825nm 10%)
- We shall be able to compute a LPF with that accuracy for *all* individual spatial elements in specified CS region
- *Spirit* of MRD-451: disk is bright enough that photometric noise is negligible and final measurement accuracy is instead limited by systematics, i.e. our ability to calibrate out instrument polarization terms
    - --> OK to demonstrate MRD-451 on a really bright disk a la HR 4796A (photometric SNR per resolution element > 100)

L2 to L3 Requirements

Level 2 requirements specify ***system level performance*** *independent of instrument design.*

- Direct Imaging
- Spectroscopy
- Extended Sources
- Polarization Measurements
- Astrometry
- Telemetry
- Polarization errors
- Pointing Jitter

Level 2 Technology Requirements

Level 3/4 Requirements

- Instrument Contrast
- Stability
- Pointing
- Throughput
- Polarization
- Detector
- Post-Processing
- Operations

Key Driving Requirements

Jeremy's slide from SRR

LPF Estimation & Error Budget

Input to Polarizers		Instrument Response Mueller Matrix	Source Intrinsic Stokes Vector

$$\begin{bmatrix} I_{in} \\ Q_{in} \\ U_{in} \\ V_{in} \end{bmatrix} = \begin{bmatrix} \eta_I & Q \rightarrow I & U \rightarrow I & V \rightarrow I \\ IP_Q & \eta_Q & U \rightarrow Q & V \rightarrow Q \\ IP_U & Q \rightarrow U & \eta_U & V \rightarrow U \\ IP_V & Q \rightarrow V & U \rightarrow V & \eta_V \end{bmatrix} \begin{bmatrix} I_{sky} \\ Q_{sky} \\ U_{sky} \\ V_{sky} \end{bmatrix}$$

CGI only measures linear polarization (not Stokes V)

True Source Polarization Linear Fraction is $LPF_{sky} = \mathrm{sqrt}(Q_{sky}^2 + U_{sky}^2)/I_{sky}$

Estimated Source Polarization Linear Fraction (no cal) is $\widehat{LPF}_{sky} = \mathrm{sqrt}(\hat{Q}_{sky}^2 + \hat{U}_{sky}^2)/\hat{I}_{sky}$

- Where $\hat{Q}_{sky}$, $\hat{U}_{sky}$ and $\hat{I}_{sky}$ are estimated from the observed linearly polarized raw images recorded ***sequentially*** in 4 polarization states: I_0, I_{45}, I_{90}, I_{135} which are turned into observed Stokes I_{in}, Q_{in}, U_{in}
- Need to understand full $\widehat{LPF}_{sky}$ estimation process to build its error budget and the con-ops scenario
- Allocations in error budget to be checked by simulations (CODE V initial results) and lab measurements
- Assumption: disks have negligible circular polarization (V~0) → $\widehat{PLF}_{sky} = f(I_{in}, Q_{in}, U_{in},$ 9 MM coefficients)

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
DARK ENERGY • EXOPLANETS • ASTROPHYSICS

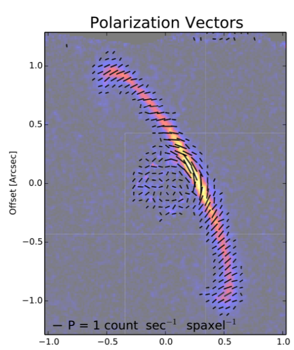
LPF Estimation & Error Budget

*Repeat on **Target** and **Reference** Star*

I_0, I_{45}, I_{90}, I_{135} raw Images

		Pre-launch vs *On-orbit* Calibrations
Clean-up Raw Frames	Regular flat fielding, Dark subtraction, bad pixel correction, frame centering	• Initial lab measurements. On-sky updates
Compute I_{in}, Q_{in}, U_{in}	Weighted sum and difference of cleaned up images, based on frame orientation Apply PZN flat fielding a la GPI?	• Needs absolute Frame orientation • Polarization flat-field measured in the lab, re-measure in orbit?
Take Out Instrument Polarization effects	Invert effect of MM coefficients (IP, Stokes throughput and cross-talk terms), assumed to be spatially invariant	• IP and IP(t) predicted by models, measured on-sky on unpolarized standards • Polarization throughput and cross-talk terms (t) predicted by models, measured on polarized standards
Apply RDI to Q and U images	Subtract Speckles using KLIP like method	• Speckles level and stability predicted by models. Reference star Stokes Q and U Images derived from linear PZN images
Compute mean Q, U and PLF image		

Target PLF Image and PZN Vectors



Perrin et al. 2015, GPI observations of HR4796A

*Lesson learned from SPHERE / IRDIS: Invert polarization effects on target and on reference star **before** applying KLIP-RDI*

Preliminary Optical Modeling results

Code V simulations of overall beam path by Jim Mcguire

- Linear polarizance (how much unpolarized light will be linear polarized) is between 0.2% and 1.5%, depending on visible wavelength.
- ***Total*** depolarization of the M Matrix (amount of depolarization of perfectly linearly polarized input, if MM coefficients can't be measured) is less than 0.4% depending on visible wavelength.
- Still finalizing estimates of linear depolarization effects
- In any case, instrument polarization effects should be very stable given the expected temperature and coating stability (n(T,t))
- Observations of (un)polarized standards* will provide measurements of the key MM coefficients and further reduce any instrumental polarization effects below 3% accuracy requirement
- The polarization measurement accuracy will likely be rather driven by drifts in the detector (gain) response and possibly changes in the instrument boresight due to polarizer wedge when switching polarizers

*: 100+ known, most with < 0.1% LPF uncertainties in the visible http://www.ukirt.hawaii.edu/instruments/irpol/irpol_stds.html

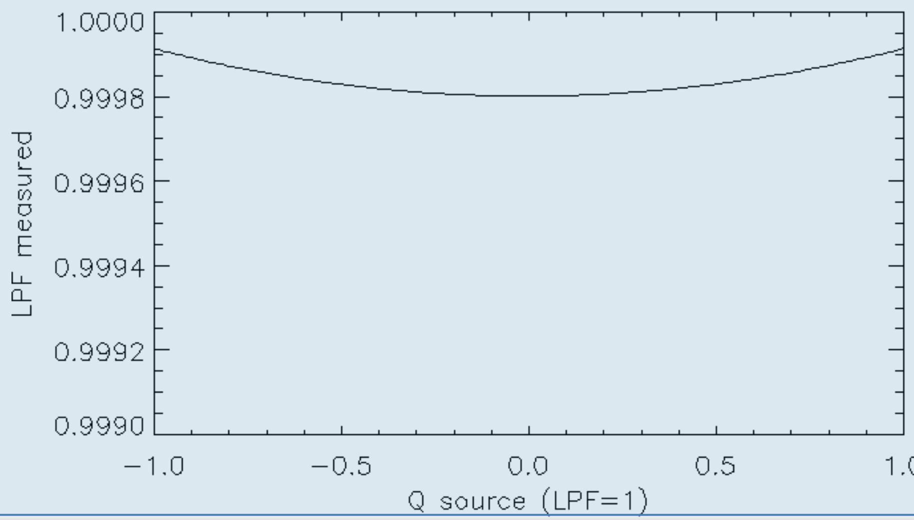
Preliminary Optical Modeling results

Jim Mcguire Code V simulations of overall beam path

Pupil averaged Mueller matrix at **550nm**:

0.57770	0.00245	0.00000	0.00000
-0.00245	-0.57765	0.00001	0.00001
0.00000	0.00000	0.57758	0.00359
0.00000	0.00000	0.00359	-0.57754

Linear polarizance: 0.00424948
Depolarization of matrix: 0.000170643
Max linear depolarization (on perfectly polarized input, without calibration): 0.0002

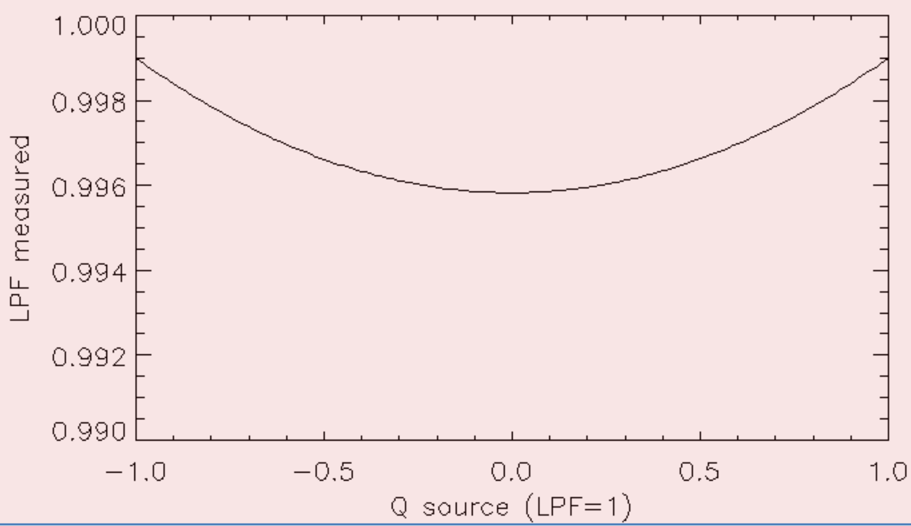


Pupil averaged Mueller matrix at **850nm**:

0.56040	0.00121	0.00000	-0.00001
-0.00121	-0.55984	-0.00013	0.00008
0.00000	-0.00013	0.55806	0.04025
0.00000	-0.00005	0.04048	-0.55758

Linear polarizance 0.00215668
Depolarization of matrix 0.00165722
Max linear depolarization (on perfectly polarized input, without calibration): 0.004

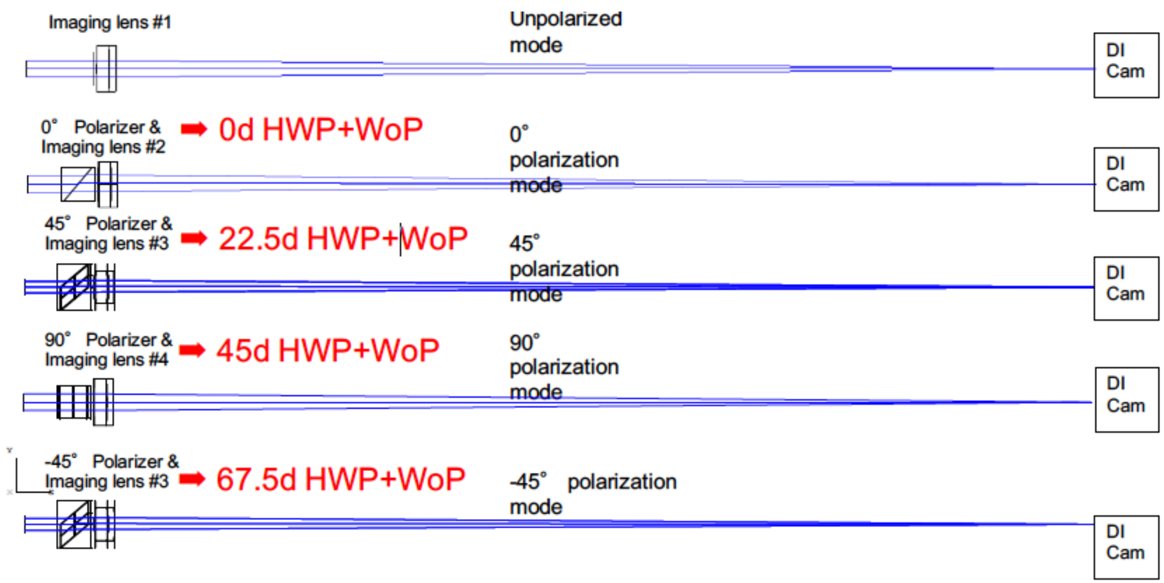
(similar behavior is found at 575nm and 825nm)



Conclusions

- Optical models indicate that no compensation of polarization effects is required to meet the 3% polarimetry requirement

- Two possible implementation strategies for CGI polarimetry mode:
  - 4 linear polarizers located in aperture wheel to be selected sequentially (JPL)
  - Rotating HWP (dedicated wheel / holder/ electronics) + fixed WP in collimated beam (JAXA)



N.B. Conversely to ground-based case, PDI is impossible with CGI → little value in imaging orthogonal polarizations at the same time

Further Comments and Questions

- Need for a polarization flat field on a calibration lamp? Pre-launch only? Talk to Max M-B

- Effect of faint dust structures (e.g. exozodi) in *reference* star images?
  - Bright ref stars used for Dark Hole digging are B stars / early A → substantial dust scattering with its own LPF and PA orientation?
  - Simulations required to understand impact of applying RDI to the target Q and U Stokes images
  - Could be an issue at the few percent LPF accuracy level while remaining undetected in Ref Q and U images (e.g disk SNR= 100 in target and faint exozodi disk SNR=3 on reference.)
  - Use Target Disk SNR >> 100, as RDI may not be needed if SNR > 100 in raw disk target images

- For measurements with finite SNR, the PLF is systematically overestimated:
  - $< Q_{in}^2 + U_{in}^2> \; = < Q_{sky}^2 + U_{sky}^2> + \sigma^2_Q + \sigma^2_U$
  - Creates an other error term that needs to be calibrated. e.g. based on the noise (scatter) of individual Q and U images or using model.
  - Or use SNR >> 100

- Con-ops
  - Observation of polarized and unpolarized standards before and after disk observations?
  - How many standards?
  - 100+ known, most with less than 0.1% PLF uncertainties in the visible
    http://www.ukirt.hawaii.edu/instruments/irpol/irpol_stds.html
  - Complete all 4 PZNs before rolling (favorite), or completing rolls before switching PZN?

Back-up Slides

Con-ops Option 1 (favorite?): completing all PZNs before rolling

Dig dark-hole on bright "nearby" reference star with telescope at roll position A

- Take Ref image at roll position A and with no polarizer in.

Slew to science target

- Take science image at roll position A, with no polarizer in.
- Take Science image at roll position A, linear polarization P1.
- Take Science image at roll position A, linear polarization P2.
- Take Science image at roll position A, linear polarization P3.
- Take Science image at roll position A, linear polarization P4.

Roll telescope to position B.

- Take Science image at roll position B, linear polarization P4.
- Take Science image at roll position B, linear polarization P3.
- Take Science image at roll position B, linear polarization P2.
- Take Science image at roll position B, linear polarization P1.
- Take Science image at roll position B, with no polarizer in.

Slew back to Ref target

- Take Ref image at roll position B, linear polarization P4.
- Take Ref image at roll position B, linear polarization P3.
- Take Ref image at roll position B, linear polarization P2.
- Take Ref image at roll position B, linear polarization P1.
- Take Ref image at roll position B, with no polarizer in.

Roll telescope to position A

- Take Ref image at roll position A, with no polarizer in.
- Take Ref image at roll position A, linear polarization P1.
- Take Ref image at roll position A, linear polarization P2.
- Take Ref image at roll position A, linear polarization P3.
- Take Ref image at roll position A, linear polarization P4.

Ref Roll A

Target Roll A
Cycle through PZNs

Target Roll B
Cycle through PZNs

Ref Roll B
Cycle through PZNs

Ref Roll A
Cycle through PZNs

Con-ops Option 2: completing rolls before switching PZN

Dig dark-hole on bright “nearby” reference star with telescope at roll position A

- Take Ref image at roll position A and with no polarizer in.
- Take Ref image at roll position B, with no polarizer in. (or do this one at the very end?)

Slew to science target

- Take science image at roll position B, with no polarizer in.
- Take Science image at roll position A, with no polarizer in.
- Take Science image at roll position A, linear polarization P1.
- Take Science image at roll position B, linear polarization P1.
- Take Science image at roll position B, linear polarization P2.
- Take Science image at roll position A, linear polarization P2.
- Take Science image at roll position A, linear polarization P3.
- Take Science image at roll position B, linear polarization P3.
- Take Science image at roll position B, linear polarization P4.
- Take Science image at roll position A, linear polarization P4.

Slew back to Ref target

- Take Ref image at roll position A, linear polarization P4.
- Take Ref image at roll position B, linear polarization P4.
- Take Ref image at roll position B, linear polarization P3.
- Take Ref image at roll position A, linear polarization P3.
- Take Ref image at roll position A, linear polarization P2.
- Take Ref image at roll position B, linear polarization P2.
- Take Ref image at roll position B, linear polarization P1.
- Take Ref image at roll position A, linear polarization P1.

Comments and Open Questions (II)

- Are CGI observations of polarization standards required?
  - GPI concentrated on IP terms (I → U or Q), calibrating them by looking at unpolarized standards and finding them to be <~1 %, with focal plane mask off (few minutes obs).
  - SPHERE only used a MM model (b/c of very strong MM dependence on parallactic angle and altitude making)

- Using ADI for disk imaging?
  - Self subtraction issues?
  - However, observing at 2 rolls provides 2 ~ independent final PLF images and/or sum them to improve SNR
  - Shall observe ref star, polarization standards as different rolls as well.
  - IP term (and other MM coefficients?) will likely change with roll angle, but not the disk PLF, allowing additional disambiguation btw instrument and astronomical PZN

- Telescope Retardance effect on PLF measurements
  - Retardance = spatially varying phase delay (ϕ) between orthogonal PZNs. How big is it?
  - Can it be assumed constant over time?
  - Can it be modeled with adequate precision or is it small enough that it does not require calibration on polarized standards?
  - Reduces measured PLF (and its SNR) by $\cos(\phi)$ which is > 0.97 if $\phi < 14$ deg
  - If disks have negligible V Stokes, the effect of retardance is only a small reduction in observed PLF and SNR